

The rapid decay phase of the afterglow as the signature of the Blandford-Znajek mechanism

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ABSTRACT

Gamma-ray bursts (GRBs) are believed to be powered by the electromagnetic extraction of spin energy from a black hole endowed with a magnetic field supported by electric currents in a surrounding disk (Blandford & Znajek 1977). A generic feature of this mechanism is that, under certain fairly general assumptions, the energy loss rate decays exponentially. In this work, we are looking precisely for such exponential decay in the light curves of long duration GRBs observed with the XRT instrument on the Swift satellite. We found out that almost 30% of XRT light curves show such behavior before they reach the afterglow plateau. According to Blandford & Znajek, the duration of the burst depends on the magnetic flux accumulated on the event horizon. This allows us to estimate the surface magnetic field of a possible progenitor. Our estimations are consistent with magnetic fields observed in Wolf-Rayet stars.

Key words: gamma-ray bursts, black hole physics, magnetic fields, Blandford-Znajek

1 INTRODUCTION

40 years after the discovery of Gamma-Ray Bursts (hereafter GRBs; Klebesadel et al. 1973) their origin remains enigmatic. The central engine, the photospheric emission, and the particular emission mechanisms are still under debate (review Kumar & Zhang 2014). It has been proposed that GRBs fall into two subcategories, short- and long-duration (Kouveliotou et al. 1993), although recently accumulated data suggests that this distinction may not be as strong as originally thought (e.g. Ghirlanda, Nava & Ghisellini 2010). For long-duration GRBs the idea of the collapse of a massive star and the formation of a stellar mass black hole (Woosley 1993; Narayan, Piran & Kumar 2001) is widely accepted. A magnetar as central engine has also been proposed (Usov 1992), and lately has been put into play for short GRBs too (Bucciantini et al. 2011). Currently, the most popular model for short GRBs is the merging of two compact objects (Rezzolla et al. 2011).

If the central engine is a black hole, there are two main physical mechanisms that may power the burst: neutrino annihilation (e. g. Chen & Beloborodov 2007), and/or the extraction of the rotational energy from a black hole (Lee et al. 2000). The first mechanism may work in some cases but fails to explain the observed energetics of Ultra Long GRB (Leng & Giannios 2014). The second involves the electro-

magnetic extraction of energy from the black hole rotation (the Blandford-Znajek mechanism, hereafter BZ; Blandford & Znajek 1977), and is widely discussed in the GRB literature (Lee et al. 2000, Wang et al. 2002, McKinney 2005, Komissarov & Barkov 2009, Nagataki 2009).

Any discussion of potential GRB models lead us to search for their signatures in GRB observations, and in particular in X-rays where a treasure load of data from the BAT and XRT instruments aboard the Swift satellite are available. X-ray GRB light curves consist of two different components: the prompt and the afterglow emission (see Fig. 1). The prompt emission is triggered by BAT, and ends when it decays below the instrument’s sensitivity limit. Anything below that limit is considered as afterglow emission which itself consists of two components separated phenomenologically (O’Brien et al. 2006; Willingale et al. 2007; Ghisellini et al. 2009). The first afterglow component seems to consist the extension of the prompt emission rapid decay phase, noticed in the first X-ray afterglow detections of Swift (Tagliaferri et al. 2005). This early steep decay phase was discussed already before Swift (Kumar & Panaitescu 2000). It was originally modelled as a residual off-axis (or high latitude) emission, and several others studied whether that model fits the observations. According to this scenario, the emission follows a ‘steepening’ power law. As we will show below, in many cases, this early steep decay phase may be fit by a single exponential. The second afterglow component starts with a plateau, continues in a power law phase, and ends with a

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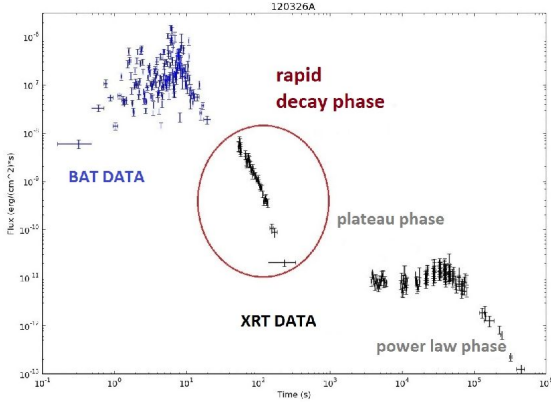


Figure 1. Lightcurve of *GRB 120326A*. Log-Log plot. Up left (in blue) are the BAT data, whereas the rest (in black) is the X-ray afterglow from XRT. We are mostly interested in the first part of the afterglow, the so-called rapid decay phase, which is suspected to be of internal origin (central engine activity). In a large number of bursts, this rapid decay phase seems to follow an exponential, compatible with black hole spindown.

final fast decay. The theoretical understanding for this second component involves energy loss through external shocks in the expanding post-explosion stellar material (Meszaros & Rees 1997).

If we believe that BZ is the mechanism that powers the burst, we should be able to find its signature in the X-ray GRB light curves which allow us to follow the central engine activity for very long times (Zhang et al. 2014). Obviously, as the black hole loses energy, it will spin down. The timescale of this procedure depends on the magnetic flux accumulated on the event horizon of the black hole and the angular velocity of the event horizon (Blandford & Znajek 1977; Lee et al. 2000). If the accumulated magnetic field exceeds magnetar values (10^{15} G), the spindown of a stellar mass black hole could last for tens of seconds. Unfortunately, due to the time it takes to reposition the satellite after the BAT triggering in order for the (much more sensitive) XRT instrument to begin observing the burst, the first 10 to 100 seconds of this phase are most of the time not observed. We will here show that, in about 30% of XRT observations where the first rapid decay afterglow phase is clearly observed, parts of it follow closely the theoretical curve (exponential) dictated by the BZ black hole spindown!

In Nathanail & Contopoulos (2015) we showed that in the limit of slow black hole rotation (i.e. less than about 10% of maximum rotation) a simple exponential can describe the energy loss rate of the BZ mechanism. We thus associated this with Ultra Long GRBs, and argued that what sets the duration of the central engine activity is the amount of magnetic flux accumulated on the event horizon of the newly formed black hole after the core collapse of a supermassive star. Thus, the surface magnetic field of the progenitor star could be crucial for the central engine activity. Based on these ideas we suggested that Ultra Long GRBs lie in the same class together with the usual Long GRBs, and their extraordinary duration may just be due to the low surface magnetic field of the progenitor star.

The present study is a follow up of the previous one, in the sense that it allows us to extend these ideas to the

full GRB population. If our magnetic field estimations have anything to do with reality, this has a straightforward implication that GRB outflows are magnetized (or at least the ones that are described by the BZ mechanism). In § 2 we give the basic equations and discuss the physical problem. In § 3 we show our results for a large sample of Swift GRBs where we focus on XRT observations that adequately follow the central engine activity. In § 4 we discuss how we can use this information to estimate the magnetic field in the vicinity of the event horizon of the black hole, and from there link it with the surface magnetic field of a possible progenitor star. Finally, we end in § 5 with a summary of our work.

2 BLACK HOLE SPIN DOWN

Let us consider a supermassive progenitor star whose core collapses and forms a rotating black hole. It is natural for the star to be magnetized. Highly conducting matter from the interior of the star will drive the advection of magnetic flux during the collapse. A certain amount of magnetic flux Ψ_m is then going to cross the horizon. An equatorial thick disk (torus) will form around the black hole due to the rotational collapse. A black hole cannot hold its own magnetic field, but the material from the thick disk will act as a barrier that will hold the magnetic flux initially advected.

As long as this is the case, the black hole will lose rotational/reducible energy at a rate

$$\dot{E} \approx -\frac{1}{6\pi^2 c} \Psi_m^2 \Omega^2, \quad (1)$$

and will thus spin down very dramatically (Blandford & Znajek 1977 for low spin parameters; Tchekhovskoy et al. 2010, Contopoulos et al. 2013, Nathanail & Contopoulos 2014 for maximally rotating black holes). Ω is the angular velocity of the black hole horizon. In principle, this procedure can extract almost all the available/reducible energy E_{rot} (Christodoulou & Ruffini 1971; Misner, Thorne & Wheeler 1973). The reader can check the above references to see that the rotational energy of a $10M_\odot$ initially maximally rotating black hole is equal to

$$E_{\text{max rot}} = 29\% Mc^2 \approx 5 \times 10^{54} \text{ erg}, \quad (2)$$

a rather extreme value for the total energy released in a GRB explosion (Komissarov, personal communication). However, if the black hole is e.g. rotating at 10% of maximum, then

$$E_{10\% \text{ of max rot}} \approx 2 \times 10^{52} \text{ erg}, \quad (3)$$

which is much more reasonable for a GRB. It is clear that if we change the mass and the spin of the black hole, the energy it can give off spans more than three orders of magnitude.

In what follows, we will assume that the newly formed black hole is slowly rotating. Under that approximation, $M \approx \text{const.}$ and

$$E_{\text{rot}} \approx \frac{1}{8} Mc^2 \left(\frac{\Omega}{\Omega_{\text{max}}} \right)^2, \quad (4)$$

where $\Omega_{\text{max}} \equiv c^3/2\mathcal{G}M$ is the angular velocity of a maximally rotating black hole, and \mathcal{G} is the gravitational constant. The black hole will, therefore, spin down as

$$\dot{E} = \frac{\mathcal{G}^2 M^3}{2c^4} \frac{d(\Omega^2)}{dt}. \quad (5)$$

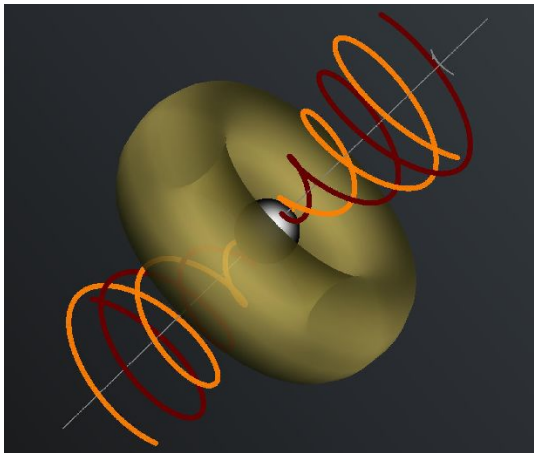


Figure 2. The structure of the magnetosphere close to the event horizon of a rotating black hole. Magnetic field lines (depicted in dark red and orange) based on the solutions of Nathanail & Contopoulos (2014). A massive torus of material (transparent) holds the magnetic flux on to the event horizon.

Equating eqs. (1) and (5) and solving for $\Omega^2 = \Omega^2(t)$, we obtain

$$\dot{E} \propto e^{-t/\tau_{\text{BZ}}} \quad (6)$$

where

$$\tau_{\text{BZ}} \equiv \frac{3c^5}{16\mathcal{G}^2 B^2 M} = 50 \left(\frac{B}{10^{15} \text{ G}} \right)^{-2} \left(\frac{M}{10M_{\odot}} \right)^{-1} \text{ sec} \quad (7)$$

is the timescale for the spinning down procedure. We have defined here a typical value for the accumulated black hole magnetic field required by the Blandford-Znajek mechanism,

$$B = \frac{\Psi_m c^4}{4\pi \mathcal{G}^2 M^2}. \quad (8)$$

B can reach very high values during the core-collapse of a massive star, and for $B \sim 10^{15} \text{ G}$, the black hole spins down in less than a hundred seconds. It is interesting to notice here that eq. (6) cannot distinguish between a black hole and a neutron star/magnetar with field lines that are held open by the surrounding material. Therefore, in principle, we cannot claim that exponential decay GRBs is definite proof for the presence of a central black hole (it is the same as pulsar spindown with braking index equal to unity). It is, however, a strong suggestion since, if a cavity forms around the central object, magnetic field lines will ‘prefer’ to form a dead zone of closed lines instead of extending to infinity. This effect will lead to a pulsar spindown different from the exponential one that we are investigating in this work. On the other hand, the exponential decay suggest the presence of very high magnetic fields that can drive an electrodynamic spindown.

It is usually argued that the balance of magnetic pressure with ram pressure from the disk can give an estimate of the possible magnetic flux accumulated around the central object. This argument is reasonable for accreting black hole systems such as AGNs and X-ray binaries, *but not* in GRB events where the black hole forms inside a super massive star. In the latter, it is very reasonable for this magnetic field to be held in place by a massive disk/torus of material that *does not accrete*. A crude calculation of the force

balance between the outward electromagnetic force, gravity and rotation yields

$$\frac{B^2}{r} r^3 \sim \frac{GMM_d}{r^2} - \frac{M_d l_d^2}{r^3} \quad (9)$$

where, M_d is the mass, l_d is angular momentum per unit mass, and r is the radius and approximate height of the torus. If the disk is rotationally supported, eq. (9) does not allow for any extra magnetic field to be held in its interior. This could be the case for a progenitor star with relatively fast rotation. If, on the other hand, the progenitor star is not rotating as fast, a slowly rotating black hole may form at the center (as we argued above), while the rest of the left over stellar material may not have enough angular momentum to form a centrifugally supported disk around it (Woosley & Heger 2006, 2012). In that case, it is natural to imagine that the equilibrium described by eq. (9) is reached. One can easily check that, in order to support a magnetic field strength of $B \sim 10^{15} \text{ G}$ for very small values of l_d , a torus of size $r \sim 2\mathcal{G}M/c^2$ and mass $M_d \sim 10^{-5} M_{\odot}$ around a $10M_{\odot}$ black hole is all that is needed. For higher values of l_d one needs a higher torus mass to hold the same value of the magnetic field. Notice that we are not presently considering the stability of this configuration against e.g. Rayleigh-Taylor instability (Contopoulos & Papadopoulos 2012). We just assume that it survives for the duration of the black hole spindown that we propose we are observing in a GRB. Obviously, if the massive disk is dispersed faster than the duration of the spindown, the accumulated magnetic flux Ψ_m will not be conserved, and the spindown evolution will not be exponential.

Other effects may too modify the black hole electromagnetic spindown, making it difficult to discern its activation and evolution. GRB events may be ‘contaminated’ by extra events that possibly take place during the spindown. One example may be fall back accretion of huge amounts of mass that could lead to a spin up of the black hole with a subsequent different spindown evolution. Moreover, the electromagnetic interaction with the torus formed around the black hole may result in an extra spindown that may too be linked to GRBs (van Putten et al. 2009).

3 XRT DATA

Up to this point we have shown that rotating black holes embedded in a strong fixed magnetic field spin down almost exponentially. It is, therefore, natural to search for exponential decay in the light curves of GRBs.

Discerning the central engine activity in a GRB light curve can be tricky. The long-term activity of the central engine must be identified. In that respect, the time estimate T_{90} can be misleading. When the signal drops out of the γ -ray band, it continues in the X-rays and this emission can still be of an internal origin. A different duration of the burst must, therefore, be defined. This was done recently by Zhang et al. (2014) who completed a comprehensive study of Swift XRT light curves that show the extended central engine activity. For all the bursts in their sample a t_{burst} is assigned. Till that time, the emission can be argued to be of internal origin (dominated by emission from a relativistic

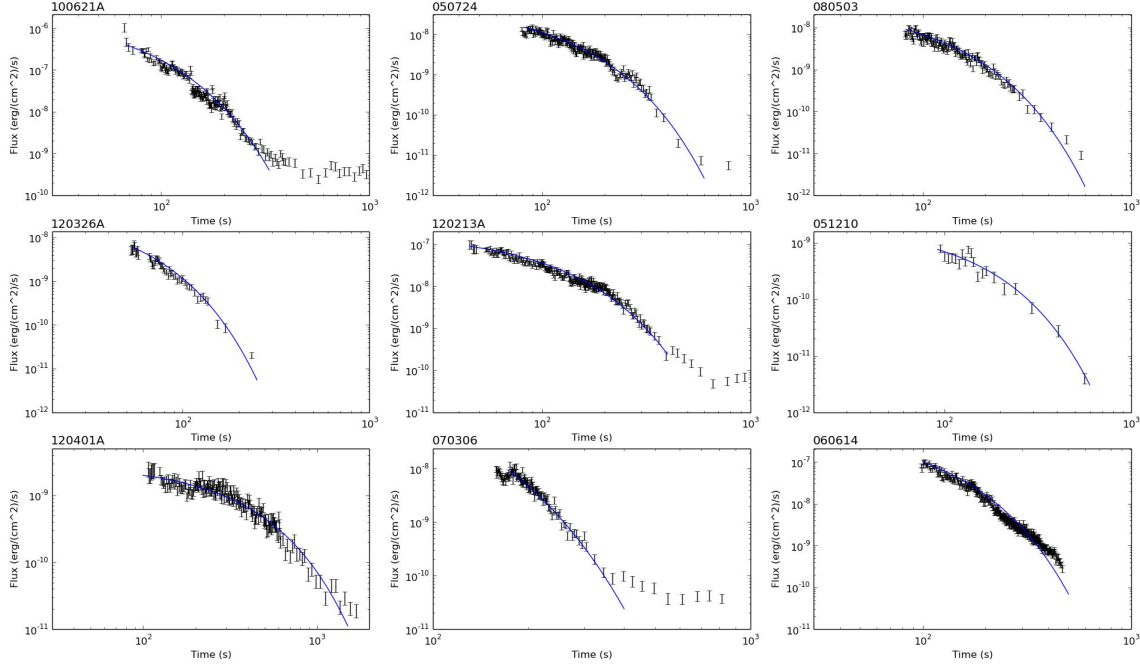


Figure 3. Nine characteristic GRBs. Log-Log plot. The green curve is the theoretical exponential black hole spindown. Energy flux at 0.3 – 10 keV. We focus in the first part of the afterglow, the rapid decay phase.

jet via an internal dissipation process), not dominated by the afterglow emission from the external shock.

We used the same GRB sample with Zhang et al. 2014. This is because we want to focus in the X-rays and we need XRT light curves with enough data to follow the central engine activity. All the XRT light curves are taken from the Swift/XRT website¹ (Evans et al. 2009) at the UK Swift Science Data Centre (UKSSDC). Our aim is to check for signs of exponential decay. While the γ -ray signal drops we are left with X-rays. Thus, in most GRBs we can follow the long term evolution of the burst in X-rays. At first the energy flux shows (in most cases) a very steep decay which is believed to be the tail of the prompt γ -ray emission. Then it enters a plateau phase and continues as a power law (Wijers et al. 1997). This extended emission can some times last up to a few weeks and is most probably associated with an external origin (external shocks, e.g. Meszaros & Rees 1997). Our aim is to check for signs of exponential decay in the first steep decay phase. It has been suggested that this rapidly declining X-ray light curve shows the evolution of the central engine activity with time (Fan & Wei 2005).

We agree with this interpretation and we believe that when we find exponential decay in this first (steep) phase we are observing the evolution of the black hole. Moreover, we argue that this may be associated with the black hole spindown discussed in § 2.

We considered every light curve from our sample and tried to fit eq. (6) over some part of it. This fit allowed us to estimate τ_{BZ} , which is a really important physical parameter. Knowing τ_{BZ} , we can estimate the strength of the magnetic field in the vicinity of the black hole. We check the quality of our fit with an R-squared statistics parameter (the closer R is to 100%, the better our exponential fits the data).

As discussed above, we want to find exponential decay in the first steep decay phase of the light curves. In order to guarantee good statistical results, we want to be able to follow this decay for more than one order of magnitude, so that we are confident we are following an exponential and not just a steep power law. Cases where data points are too few to claim good statistical results (e.g. GRBs 090418A, 130803A, 051016A, 090313 etc.) were excluded. For the ones that the rapid decay in the X-rays is less than one order of magnitude (e.g. GRBs 100219A, 091020, 090904B, 090515, etc.) we may have lost the first afterglow phase and thus are

¹ <http://www.wift.ac.uk/xrt.curves/>

left out. Furthermore, GRBs with an irregular distribution of data points (e.g. GRB 050915A) (i.e. with extra complex physical process going on in parallel) are left undefined.

All these features discussed here have been categorized in a phenomenological manner which identified three components in the afterglow: rapid decay followed by a plateau and a final power law phase (Ghisellini et al. 2009). In this way, we can identify several X-ray flares that require extended central engine activity. Going back to our theoretical model we remind the reader that many effects (such as mass infalls that may result in sudden black hole spin ups) can modify the black hole electromagnetic spindown, making it difficult to discern its activation and evolution. Such secondary events will yield secondary flares, as is frequently seen in GRB light curves (Wu et al. 2013). There are cases in which, after a big flare, the emission shows a steep decay more than two orders of magnitude (e.g. GRB 121027A). It is very interesting that this rapid emission decay after the flare is also exponential. We have found several events that conform to this picture, and we plan to discuss them in more detail elsewhere. There are also some GRBs with minor flares that do not disrupt a single exponential fit. In these GRBs R-squared is less than 70 – 80% (e.g. GRB 111103B) and its not clear whether we are following a black hole spinning down or not. Another physical possibility that would mask the exponential decay is if the surrounding disk disperses faster than the duration of the spindown. In that case, the accumulated magnetic flux Ψ_m will not be conserved, and the spindown evolution will not be exponential. We decided to focus only on GRBs with a single emission decay event. We thus formulated the following empirical criteria that characterize our good sample: (i) emission decay more than one order of magnitude, (ii) full (not sparse) sampling of the light curve in the time interval that we follow the spindown and (iii) the steep decay emission phase to be without continuous big flares. No strong conclusions on the central engine activity can be extracted for those few GRBs (~ 33) with not enough data in the steep decay phase.

By fitting eq. (6) to the light curve, we find τ_{BZ} for every GRB listed in tables 1 & 2. From the primary sample of 343 GRBs, we excluded 33 objects with low number of data in the rapid decay phase, and were left with 310 GRBs. From these GRBs, 60 ($\sim 20\%$) have a very good exponentially decaying emission event, with R -squared over 90% for most of them. This can be our golden sample. In table 1 we show the τ_{BZ} and the R -squared that we obtained for these objects. In all these events we can follow the exponential decay (black hole spindown) for more than two orders of magnitude combined with a very good fitting result (R -squared more than 90%). There are many GRBs (~ 31) where the rapid decay phase is really small and the lightcurve enters quickly in a plateau phase or go straight to the plateau phase (~ 33). In these events, the rapid decay can be less than an order of magnitude, thus we cannot support an exponential.

In table 2 we list those 23 objects that have flares with a subsequent exponential decay. A representative example from this class is GRB 121027 (shown in fig. 5) where the X-ray lightcurve starts with an exponential (not disrupted by a small flare around ~ 300 sec), and after a big flare at around ~ 5000 sec (energy flux increases more than two orders of magnitude) it continues again with an exponential. This big flaring activity may be understood as black hole spinning up

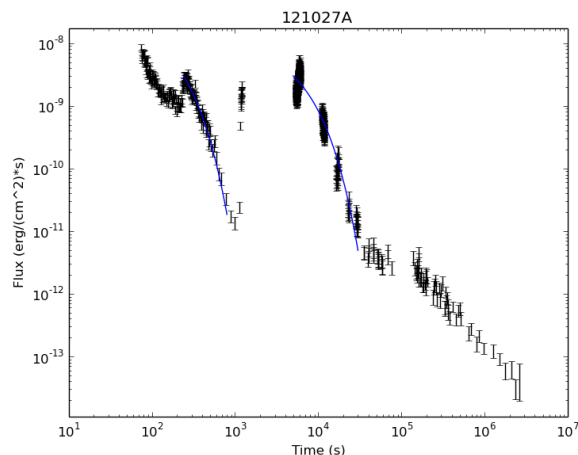


Figure 5. GRB 121027A, a huge X-ray flare made this one exceptional. It is interesting to see that after the flare, the decay is exponential.

because of large amount of mass infall. Altogether, 27%(83) of GRBs show an exponential decay in the first phase of the afterglow. There are another 35 GRBs with many small flares in their lightcurves, for which no conclusion is reached.

We have to state here that we found 28 GRBs in which the whole afterglow can be fitted with a single power law. For the remaining 100 objects no strong conclusion could be reached. There is a possibility that XRT failed to catch their rapid decay phase. Moreover, a further spindown of the central object may be hidden behind a stronger emission of external origin.

4 THE MAGNETIC FIELD OF THE PROGENITOR STAR

In the previous section we showed that there are several GRBs with clear signs of exponential decay in their light curves. We have related this decay to the spindown of a newly formed black hole (most probably slowly rotating). The spindown is electromagnetic, and the timescale τ_{BZ} gives us an estimate of the magnetic field strength on the event horizon of the black hole.

Some GRBs were reported with ultra long central engine activity (Levan et al. 2014). In this small population we also found clear signs of exponential decay which we associated with black hole spindown (Nathanail & Contopoulos

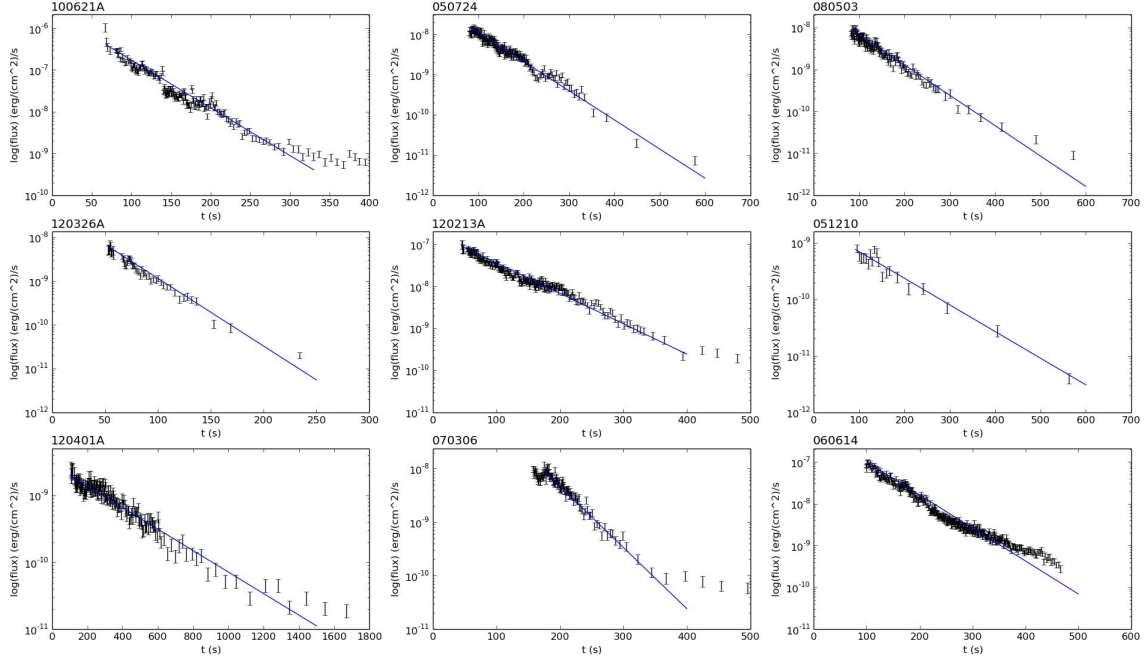


Figure 4. Same as Fig. 3 in Log-Linear scale. Notice that in Log-Linear plots an exponential is shown as a straight line. Energy flux at 0.3 – 10 keV. We focus in the first part of the afterglow, the rapid decay phase.

Table 1. The 60 GRBs with a clear exponential decay

| Fitted Parameter | | | | | | | | |
|------------------|--------------------------|--------------|---------|--------------------------|--------------|---------|--------------------------|--------------|
| GRB | τ_{BZ} (sec) | R -squared | GRB | τ_{BZ} (sec) | R -squared | GRB | τ_{BZ} (sec) | R -squared |
| 050716 | 140 (± 4) | 0.929 | 050724 | 60 (± 4) | 0.948 | 050915B | 31 (± 4) | 0.916 |
| 051210 | 90 (± 8) | 0.741 | 060413 | 82 (± 13) | 0.800 | 060614 | 55 (± 2) | 0.988 |
| 060708 | 25 (± 3) | 0.945 | 060729 | 35 (± 3) | 0.975 | 061110A | 50 (± 4) | 0.921 |
| 061121 | 14 (± 1) | 0.973 | 061222A | 34 (± 4) | 0.849 | 070306 | 38 (± 3) | 0.928 |
| 070420 | 36 (± 3) | 0.896 | 070621 | 50 (± 6) | 0.897 | 071227 | 72 (± 20) | 0.726 |
| 080205 | 32 (± 4) | 0.959 | 080229A | 33 (± 5) | 0.940 | 080503 | 60 (± 4) | 0.920 |
| 081028 | 145 (± 25) | 0.830 | 081128 | 50 (± 5) | 0.973 | 081221 | 32 (± 2) | 0.918 |
| 081230 | 17 (± 2) | 0.958 | 090111 | 28 (± 2) | 0.929 | 090404 | 28 (± 2) | 0.972 |
| 090618 | 18 (± 2) | 0.904 | 091026 | 40 (± 3) | 0.925 | 091029 | 30 (± 2) | 0.936 |
| 091104 | 70 (± 10) | 0.801 | 100418A | 30 (± 3) | 0.948 | 100425A | 25 (± 3) | 0.826 |
| 100514A | 32 (± 2) | 0.944 | 100522A | 18 (± 3) | 0.965 | 100526A | 57 (± 5) | 0.949 |
| 100615A | 26 (± 3) | 0.945 | 100621A | 38 (± 2) | 0.989 | 100725A | 95 (± 7) | 0.871 |
| 101030A | 36 (± 3) | 0.926 | 101213A | 75 (± 9) | 0.902 | 101225A | 6000 (± 0) | 0.900 |
| 110210A | 90 (± 8) | 0.927 | 110414A | 30 (± 6) | 0.906 | 110420A | 26 (± 2) | 0.939 |
| 110808A | 50 (± 6) | 0.946 | 111123A | 130 (± 6) | 0.968 | 111209A | 4900 (± 500) | 0.900 |
| 111225A | 110 (± 18) | 0.826 | 120106A | 21 (± 1) | 0.929 | 120116A | 39 (± 6) | 0.900 |
| 120213A | 60 (± 5) | 0.982 | 120215A | 65 (± 8) | 0.982 | 120324A | 44 (± 4) | 0.902 |
| 120326A | 28 (± 2) | 0.959 | 120401A | 270 (± 30) | 0.917 | 120514A | 30 (± 4) | 0.909 |
| 120922A | 75 (± 3) | 0.960 | 121108A | 15 (± 2) | 0.936 | 130315A | 80 (± 5) | 0.983 |
| 130528A | 25 (± 2) | 0.924 | 131018A | 50 (± 13) | 0.794 | 131127A | 30 (± 5) | 0.940 |

2015). We were thus able to link the magnetic flux accumulated on the event horizon to the surface magnetic field of the progenitor star. It is natural to extend this discussion to the long duration GRBs of our present sample. As before, we will assume that a $10M_{\odot}$ black hole forms at the center. This is a natural choice if the progenitor star mass is $25 - 40 M_{\odot}$ (Heger et al. 2003). The timescales τ_{BZ} that we have found span a range between 11 and 6000 sec. Notice that these values are not corrected for cosmological redshift. Applying them to eq. (7), we find that the magnetic field (uncorrected for redshift) on the event horizon varies between

$$B_H \approx 10^{14} \text{ and } 10^{15} \text{ G.} \quad (10)$$

This magnetic field will drive the black hole spindown, in agreement with observations that show signs of magnetically dominated outflows from GRBs (e.g. Guiriec et al. 2014). The black hole event horizon for a slowly rotating $10M_{\odot}$ black hole is at $r_H \approx 3 \times 10^6$ cm. During the collapse, the magnetic field is carried along by the conducting matter of the stellar interior, and flux conservation implies

$$Br^2 = B_{\star} r_{\star}^2, \quad (11)$$

where B_{\star} and r_{\star} are the surface magnetic field and the radius of the star respectively. A typical radius for a Wolf-Rayet star is 10^{12} cm (Crowther 2007), in which case eq. (11) yields

$$B_{\star} \sim 10^3 - 10^4 \text{ G.} \quad (12)$$

Let us now see how the above estimates compare with observations of magnetic fields in Wolf-Rayet stars. At visible wavelengths, their stellar surface is hidden by a dense nebula. Magnetic field values of $22 - 128$ G have been reported in their stellar winds through measurements of emission lines (de la Chevrotiere et al. 2014). The corresponding surface value of the magnetic field must be much higher than the observed estimated values. Assuming that the surface field is stretched as $1/r^2$ with distance in the wind, our magnetic field estimate of eq. (12) ten stellar radii from the surface would yield 10 to 100 G, in agreement with the observations. Notice that our magnetic field estimates did not take into account a $(1+z)^{1/2}$ correction factor due to the cosmological redshift z . Notice that they also did not take into account possible dynamo magnetic field amplification under the cataclysmic conditions in the collapsing environment, as discussed in the literature (Obergaulinger et al. 2009). If we assume an extra three orders dynamo field amplification our estimate of the surface magnetic field could be as low as $B_{\star} \sim 1$ G.

The above estimates were obtained with the physical image of a Wolf-Rayet star discussed extensively in the GRB literature (Woosley & Bloom 2006). Even if the type of the progenitor changes, our estimate of its magnetic field still holds and can be slightly corrected (depending on the radius of the star). The main point here is that the duration of these bursts depends on the magnetic field of the progenitor star. The idea that magnetic flux is the principal parameter that sets the luminosity of a GRB is discussed also in Tchekhovskoy & Giannios (2015), although in their case the central engine turns-off when the steep decline stage starts.

5 SUMMARY

We have shown that a newly formed black hole resulting from the core collapse of a supermassive star may be slowly rotating and still power a GRB. The magnetic flux accumulated on the event horizon of the black hole can drive the extraction of the black hole rotational energy through the Blandford-Znajek mechanism. We argue that it is possible to hold this magnetic flux for the duration of the burst even without accretion onto the black hole. In that case, the electrodynamic energy release decays exponentially.

In the present study we extended the analysis of Nathanail & Contopoulos (2015) on Ultra Long GRBs to a much larger sample of Long GRBs. As before, in order to follow the central engine activity as far as possible, we focused on the XRT X-ray band. From a sample of 292 GRBs, 60 show a clear exponential decay and 25 also proceed with an exponential decay after a flare. In total, 29% of the events in our sample contain a clear exponentially decaying part. We (as well as others before us) propose that the rapid decay phase of the X-ray light curves of Long GRBs is of internal origin, i.e. it represents the rapid decay of the central engine activity. As in the case of Ultra Long GRBs, we propose to associate this rapid decay with the exponential spindown of the central black hole. As a result, we suggest that the duration of a GRB depends closely on the magnetic flux accumulated on the event horizon. This in turn can be directly associated, through flux conservation, with the surface magnetic field of the progenitor star. We have to state that in some short GRBs the rapid decay phase is exponential, this needs careful work to be understood.

A final note on timescales is in order here. In all the bursts with signs of exponential decay, the time that this decay stops is defined as t_{burst} (Zhang et al. 2014) which, in general, has nothing to do with our decay timescale τ_{BZ} . The central engine may continue to give off energy, but a different emission mechanism (e.g. external shocks) will eventually overpower its emission.

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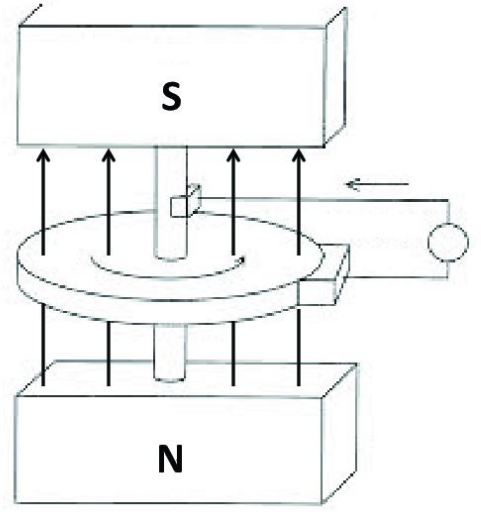
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Table 2. The 23 GRBs with a clear exponential decay after a flare

| Fitted Parameter | | | | | | | | |
|------------------|--------------------------|------------------|---------------------|--------------------------|------------------|---------------------|--------------------------|------------------|
| <i>GRB</i> | τ_{BZ} (sec) | <i>R-squared</i> | <i>GRB</i> | τ_{BZ} (sec) | <i>R-squared</i> | <i>GRB</i> | τ_{BZ} (sec) | <i>R-squared</i> |
| 050502 <i>B</i> | 95 (± 8) | 0.928 | 060929 | 90 (± 14) | 0.899 | 061202 | 55 (± 3) | 0.923 |
| 070720 <i>B</i> | 55 (± 7) | 0.905 | 080212 | 47 (± 4) | 0.944 | 080325 | 95 (± 8) | 0.927 |
| 090621 <i>A</i> | 27 (± 3) | 0.921 | 090904 | 40 (± 6) | 0.952 | 100619 <i>A</i> | 11 (± 1) | 0.965 |
| 100704 <i>A</i> | 36 (± 3) | 0.960 | 100727 <i>A</i> | 45 (± 6) | 0.911 | 100802 <i>A</i> | 110 (± 17) | 0.910 |
| 100814 <i>A</i> | 65 (± 5) | 0.936 | 100902 <i>A</i> | 37 (± 3) | 0.981 | 100906 <i>A</i> | 12 (± 1) | 0.985 |
| 120308 <i>A</i> | 52 (± 4) | 0.910 | 121027 <i>A</i> (1) | 110 (± 6) | 0.929 | 121027 <i>A</i> (2) | 3800(± 300) | 0.700 |
| 121123 <i>A</i> | 110 (± 12) | 0.979 | 121217 <i>A</i> | 80 (± 8) | 0.917 | 131030 <i>A</i> | 25 (± 2) | 0.948 |
| 140108 <i>A</i> | 12 (± 2) | 0.944 | 140114 <i>A</i> | 65 (± 4) | 0.941 | | | |

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**Figure 6.** Faraday disk with conducting path and load that allow it to spin down exponentially. Vertical arrows: magnetic field.

APPENDIX

The electromagnetic black hole spindown is conceptually similar to the spindown of the so-called Faraday disk, a conducting disk of radius r , mass M and angular velocity Ω threaded by a certain amount of magnetic flux Ψ_m and magnetic field B (Fig. 6). The magnetic field is not generated by the disk itself, but is generated and held in place by an external magnet. If we assume the existence of a conducting path for electric currents to close over the surface of the disk, the spindown rate is proportional to $-\Psi_m^2 \Omega^2$, and the disk loses rotational kinetic energy at a rate proportional to $Mr^2 \Omega \dot{\Omega}$. Equating the latter two expressions, we deduce that the Faraday disk spins down exponentially as $\Omega(t) \propto e^{-t/2\tau}$, and thus loses rotational energy at a rate $\dot{E}(t) \propto e^{-t/\tau}$.

$$(13)$$

The characteristic decay timescale τ is proportional to the mass and the square of the radius, and inversely proportional to the square of the total accumulated magnetic flux, namely

$$\tau \propto Mr^2 / \Psi_m^2 \propto M / r^2 B^2 . \quad (14)$$